

EVOLUTION OF PRE-MAIN SEQUENCE ACCRETION DISKS

Grant NAG5-9670

Annual Report #4

For the period 1 July 2003 through 30 June 2004

Principal Investigator

Dr. Lee W. Hartmann

April 2004

Prepared for

National Aeronautics and Space Administration
Goddard Space Flight Center, Greenbelt, MD

Smithsonian Institution
Astrophysical Observatory
Cambridge, Massachusetts 02138

<p>The Smithsonian Astrophysical Observatory is a member of the Harvard-Smithsonian Center for Astrophysics</p>

Annual Report for NAG5-9670

Evolution of Pre-Main Sequence Accretion Disks

L. Hartmann, PI

Introduction

The aim of this project is to develop a comprehensive global picture of the physical conditions in, and evolutionary timescales of, pre-main sequence accretion disks. The results of this work will help constrain the initial conditions for planet formation.

To this end we are developing much larger samples of 3-10 Myr-old stars to provide better empirical constraints on protoplanetary disk evolution; measuring disk accretion rates in these systems; and constructing detailed model disk structures consistent with observations to infer physical conditions such as grain growth in protoplanetary disks.

1. Past year

i. Cluster survey- ground-based data

We are continuing our observational program to identify star clusters with ages of 3-10 Myr which are sufficiently populous to provide good statistical information on disk properties as a function of stellar mass and age. We have identified two such clusters, Tr 37 and NGC 7160, which lie in the Cep OB2 association at a distance of approximately 900 pc.

We recently completed a study of the massive and intermediate-mass stars in Tr 37 (Contreras et al. 2002, AJ, 124, 1585). The photometry and spectroscopy help to refine the membership, reddening ($A_V \sim 1.5 \pm 0.5$), and distance modulus ($m - M = 9.7 \pm 0.2$) to this cluster. Only three new emission-line stars were found in our sample, resulting in a total of four stars in the cluster with emission lines and spectral type earlier than G. One of these emission-line stars, LkH α 349, is probably not a member of the central cluster, as it lies within a dark globule on the periphery of the H II region IC 1396 (see also Figure 2). Three of the four emission line stars show near-infrared excesses characteristic of circumstellar disks. Thus, at an age of about 3 Myr, as estimated from the expansion age of molecular material around the cluster, emission-line phenomena driven by disk accretion are extremely rare through spectral types F (masses $\gtrsim 1.5M_\odot$).

Using CCD photometry from 4-shooter mosaic camera on the SAO 1.5m meter telescope on Mt. Hopkins, we identified candidate cluster members from their positions in the color-magnitude diagram, and then obtained followup spectroscopy for these candidates using the Hydra multifiber bench spectrograph on the WIYN telescope on Kitt Peak. Using H α emission and Li I absorption indicators, we were able to identify low-mass members in these clusters and confirm the ages discussed above.

A remarkable and unexpected result is that we found a highly non-uniform distribution of low-mass stars in Tr 37, which seems to differ from that of the intermediate-mass stars (Figure

1). The origin of this distribution is not understood. One possibility is that stars near the central O7 star have had their disks evaporated; thus, only weak-emission, non-accreting stars are in the cluster center, and such stars would be difficult for us to detect given the strong nebular H α emission. This does not explain, however, why the stars would be strongly concentrated to the west. It appears that this cluster is much more dispersed than many, which may lead to insights into the range of conditions leading to massive star formation- specifically, that massive stars may not necessarily be formed at the bottoms of deep cluster gravitational potential wells, as assumed for example in theories of competitive accretion.

The paper reporting these results has been accepted for publication (Sicilia-Aguilar *et al.* 2004).

Followup observations using the new Hectospec multiobject spectrograph on the MMT on Mt. Hopkins are scheduled for June 2004. These observations will allow us to rapidly survey the clusters to fainter targets and to do better subtraction nebular emission. The goal is to identify all of the weak-emission T Tauri members of these clusters - that is, the cluster members that do not have accretion disks. Optical spectra are the only way that we can identify such systems, through detection of weak H α emission and Li I absorption.

ii. Infrared excesses in Tr 37

As part of the effort to understand protoplanetary disc evolution in young clusters, described in the previous section, we have obtained Spitzer Space Telescope Observations of Tr 37 and NGC 7160. The Infrared Array Camera (IRAC) data is in hand for both clusters (Figure 2), and we have begun reducing and analyzing the data. The four IRAC bands, spanning the range from 3.6 μ m to 8 μ m, are ideal for detecting infrared excess emission from inner disks to extremely sensitive levels. An initial reduction aimed at identifying the stars with disks (Figure 3) shows the same concentration to the west of the O6 star that we inferred from the ground-based data. Further analysis is being undertaken of these observations. In addition, we have 24 μ m observations from the MIPS instrument on Spitzer for NGC 7160 that will be analyzed; corresponding observations for Tr 37 are expected to be obtained sometime during summer 2004.

iii. Disk accretion

In a recently published paper (Muzerolle *et al.* 2003), we studied disk accretion in very low mass stars. Using limits on continuum veiling and modelling H α line emission which arises in magnetospheric accretion columns, we showed that very low mass T Tauri stars accrete at very low rates, $10^{-12} < \dot{M} < 10^{-9} M_{\odot} \text{ yr}^{-1}$, with a clear dependence on mass.

The mass dependence of accretion was more explicitly examined in a recently published paper (Muzerolle *et al.* 2004) in which we added results from intermediate-mass stars. Over the entire range from 0.04 – 4 M_{\odot} , we find increasing mass accretion rates with increasing mass. The overall trend is roughly $\dot{M} \propto M^{2.3}$, with a large scatter at each mass. The physical origin of this relation is not clear; standard viscous accretion disk models predict some correlation but not as steep a relation as we find. We suggest that X-ray ionization of the disk may provide

an additional mass-dependent effect on the angular momentum transport needed for accretion; this possibility needs to be explored with further theoretical and observational work.

iv. Herbig Ae/Be stars

In a recently published paper (Hernandez *et al.* 2004), we presented a study of the optical spectra of Herbig Ae/Be stars, the intermediate-mass counterparts of the low-mass T Tauri stars. Accurate spectral types were presented and compared with observed optical photometry to confirm previous findings of high values of total-to-selective extinction ($R_V \sim 5$). Using higher values of R_V than often adopted, we find that the vast majority of H Ae/Be stars appear younger, more consistent with being pre-main sequence objects.

v. McNeil's nebula

In a recently published paper (Briceno *et al.* 2004) we presented a study of the newly-discovered eruptive young star in McNeil's nebula. We derive photometry spanning the preoutburst state and the brightening itself, which is a unique record including 14 epochs and spanning a timescale of about 5 years. We constrain the beginning of the outburst at some time between 2003 October 28 and November 15. The light curve of the object at the vertex of the nebula, the likely exciting source of the outburst, reveals that it has brightened 5 mag in about 4 months. The timescale for the nebula to develop is consistent with the light-travel time, indicating that we are observing light from the central source scattered by the ambient cloud into the line of sight. We also show recent FLWO optical spectroscopy of the exciting source and of the nearby HH 22. The spectrum of the source is highly reddened; in contrast, the spectrum of HH 22 shows a shock spectrum superposed on a continuum, most likely the result of reflected light from the exciting source reaching the HH object through a much less reddened path. The blue portion of this spectrum is consistent with an early B spectral type, similar to the early outburst spectrum of the FU Orionis variable star V1057 Cygni. These observations constitute a unique dataset for understanding eruptive phenomena in early stellar evolution.

2. Final year

All of the observations for the cluster study – the main part of this program – should be completed by some time during the summer of 2004. The Hectospec observations should be obtained in June, as described above, and these will enable us to develop complete cluster membership lists to near the brown-dwarf limit, by identifying $H\alpha$ emission sources (with Li absorption). Most of the Spitzer Space Telescope observations are in hand, and the rest should be obtained during summer 2004 as well. These data will enable us to unambiguously detect inner disk emission from cluster members to sensitive limits. In combination, these data will enable us to infer a complete picture of disk evolution in these clusters for stars with ages between 1 and 10 Myr. As an added bonus we will begin exploring the asymmetric distribution of stars in Tr 37 to see what implications this has for models of cluster formation.

The photometric and spectroscopic reductions and analysis are being performed by CfA predoctoral fellow Aurora Sicilia Aguilar as part of her thesis research. We expect data reduction to be completed by the end of summer 2004; the corresponding scholarly papers and the thesis should be completed by the end of calendar year 2004.

Papers supported by this grant during last year

Briceño, C., et al. 2004, ApJL, 606, L123

Hartmann, L. 2003, ApJ, 585, 398

Hernández, J., Calvet, N., Briceño, C., Hartmann, L., & Berlind, P. 2004, AJ, 127, 1682

Muzerolle, J., Hillenbrand, L., Calvet, N., Briceño, C., & Hartmann, L. 2003, ApJ, 592, 266

Muzerolle, J., Calvet, N., Hartmann, L., Briceño, C., Hillenbrand, L., & Hernandez, J. 2004,
in press

Osorio, M., D'Alessio, P., Muzerolle, J., Calvet, N., & Hartmann, L. 2003, ApJ, 586, 1148

Reipurth, B., Hartmann, L., Kenyon, S.J., Smette, A., & Bouchet P. 2002, AJ, 124, 2194

Sicilia-Aguilar, A., Hartmann, L., Briceño, C., Muzerolle, J., & Calvet, N. 2004, AJ, in press

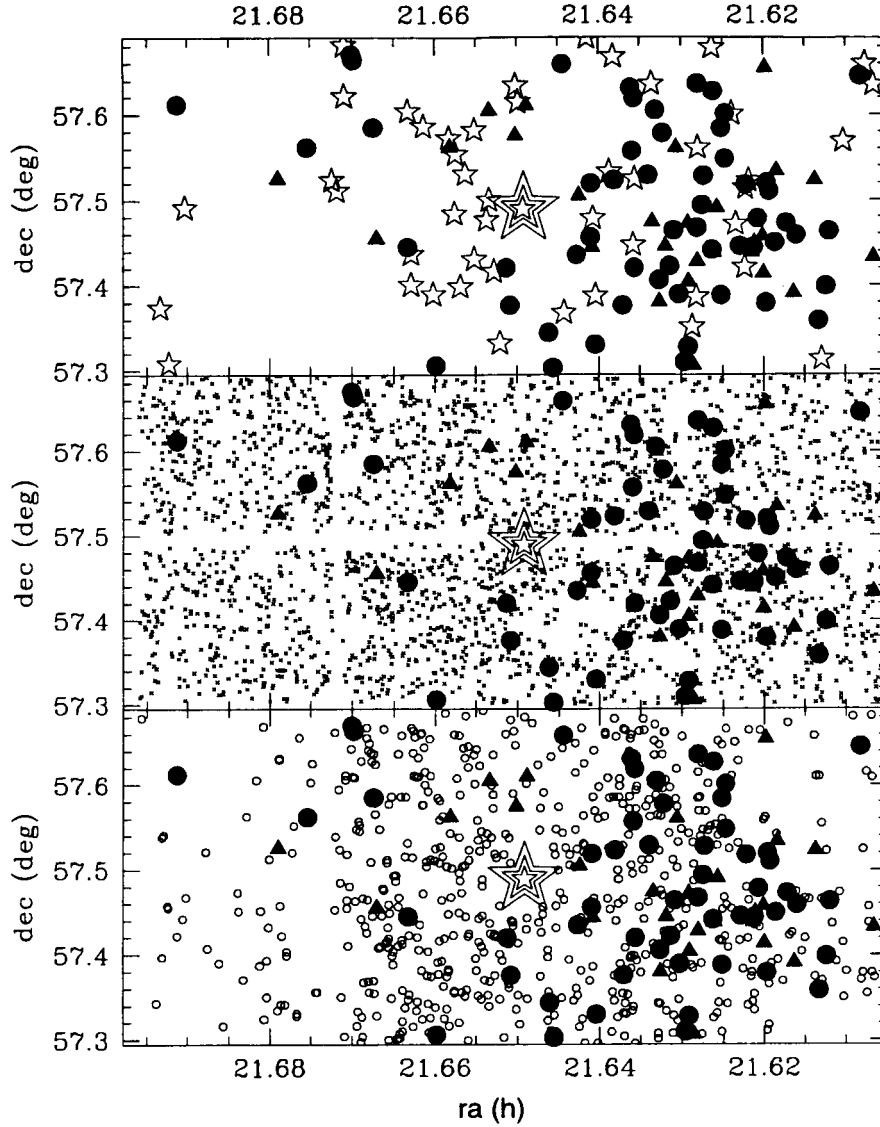


Figure 1: Spatial distribution of stars in Tr 37, as inferred from ground-based data. Large star: O6 central star HD206267. Small stars: B and A cluster members. Black large circles: CTTS. Black large triangles: WTTS. Upper figure: Distribution of cluster TTS versus high and intermediate mass stars. Middle figure: Distribution of candidates (small crosses) versus TTS. Lower figure: Distribution of observed targets (small open circles) versus TTS. The asymmetry of TTS vs. higher mass members is clear from the upper panel. The lower panel shows the non-uniform sampling along the East-West direction. Targets near the O star suffer from strong nebular $H\alpha$ contamination, making it difficult to find weak emission members.



Figure 2: Channel 1 ($3.6\ \mu\text{m}$) mosaic image from the IRAC instrument on Spitzer Space Telescope of the young cluster Tr 37. The extended object to the upper left is a dusty globule of molecular gas which harbors very young stars.

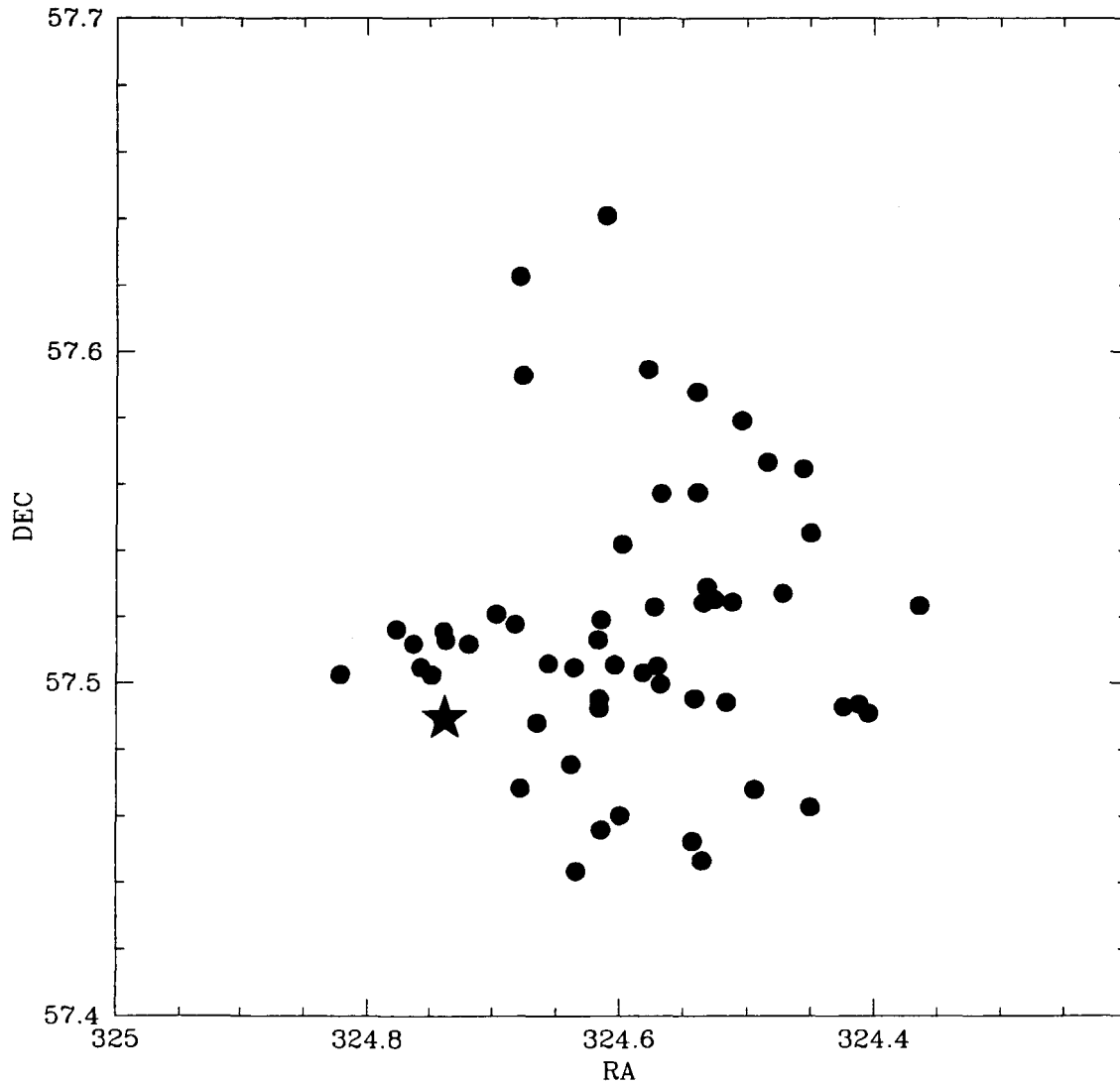


Figure 3: Positions of young stars in Tr 37 initially detected with excesses between 3.6 and 4.5 μm , and detected in all bands with IRAC (see text). The star denotes the position of the O6 star HD 206267. The general spatial asymmetry of the infrared-excess stars (i.e., the stars with inner accretion disks) confirms the asymmetrical distribution of such stars with respect to the O6 star inferred from ground-based data.